INFLUENCE OF ELECTRIC CURRENTS AND FIELDS ON THE KINETICS AND MICROSTRUCTURE OF PHASE TRANSFORMATIONS IN METALS AND CERAMICS

Final Report

Hans Conrad

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13. ABSTRACT *(Maximum 200 words)*

Electropulsing: The decrease in the flow stress of FCC metals produced by individual high density electropulses was mainly due to an increase in the pre-exponential in the Arrhenius rate equation for plastic flow. An order of magnitude decrease in the colony size of eutectic Pb-Sn castings was produced by electropulsing, the effect being in accord with an increased nucleation rate. Electropulsing caused the precipitation of nanometer α-Fe particles from the matrix of amorphous Fe-Si-B alloys at temperatures well below the normal crystallization temperature.

Electric Field: An external electric field of 1 kV/cm applied during the superplastic deformation of 7475 Al alloy enhanced the formation of whiskers having elongations greater than 1000%. The application of an electric field of ~ 1 kV/cm during the deformation of polycrystalline NaCl at 0.28 – 0.75 T_M gave the following: (a) reduced the flow stress, (b) raised the brittle-to-ductile transition temperature and (c) increased the elongation. The effect of the field at $T < 0.65\ T_M$

14. SUBJECT TERMS
Electric field, electric current, magnetic field, superplastic deformation, flow stress, fracture, ductility, fatigue, grain growth, cavitation.

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<u>Magnetopulsing</u>: The fatigue life of a low-carbon steel was prolonged by exposing the specimen to magnetic pulses after cycling to approximately half of its normal fatigue life.

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Key Words

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INFLUENCE OF ELECTRIC CURRENTS AND FIELDS ON THE KINETICS AND MICROSTRUCTURE OF PHASE TRANSFORMATIONS IN METALS AND CERAMICS

1. Statement of the Problem Studied

The external parameters generally considered in properties and processing of materials are temperature, time and pressure or stress. Usually neglected are the effects of electrical and magnetic fields. However, often such fields can have a *significant* influence, especially when applied concurrently with the more common parameters. Prior work by the principal investigator and his associates under ARO sponsorship [1,2] has demonstrated this to be the case for a number of metals and alloys. For example, it was found that the application of an external electric field of ~ 1 kV/cm (with a current of ~ 1 mA) reduced the flow stress and retarded grain growth and cavitation during the superplastic deformation of 7475 alloy and moreover it retarded the recovery and recrystallization of cold worked Al and Cu. Further, an external electric field increased the hardenability of a low-alloy, high-carbon steel and retarded quench aging in a low-carbon steel. The application of high density electric current pulses (10^3 – 10^5 A/cm^2 with ~ 50 μs duration) produced the following effects: (a) significantly reduced the flow stress of a number of metals in addition to any Joule heating effects, (b) enhanced the fatigue life of Cu, (c) enhanced the recovery and recrystallization of cold worked Al, Cu and Ni_3Al and (d) reduced the colony (grain) size of Pb-Sn alloys. Further, a dc current of ~ 10^3 A/cm^2 enhanced quench aging in a low-carbon steel, while an a.c. current of the proper frequency retarded the aging. These results established that the concurrent application of electric fields and currents offer the

possibility of increasing the efficiency and effectiveness of metal processing operations and of improving the resulting properties. Moreover, they provide useful information regarding the effects of electric fields and currents on the behavior and properties of metals, which information is important regarding their use in microelectronic packages and in such electrical systems as railguns, levitated trains and electrical machinery.

Additional studies are however required to substantiate and develop in more detail the atomic mechanisms proposed in the prior work [1,2] for the effects of electric fields and currents on metal properties and behavior. This then was one objective of the present study. A second objective was to extend the studies to include ceramic materials, since this class of materials is finding increasing application in defense and civilian components and systems. In view of the ionic and covalent nature of the atomic bonding in this class of materials it was expected that they would respond to an electric field. A focus of the research was therefore to determine the influence of the type of atomic bonding on the response to an electric field.

2. Summary of Most Important Results

2.1 High Density Electric Current Pulses

2.1.1 Mechanical Properties

It was determined that the factors contributing to the decrease in the flow stress of the FCC metals Ag, Al and Cu produced by high density electric current pulses at 77–300K depended on the stacking fault energy [3]. The largest effect of the current was on the pre-exponential of the Arrhenius rate equation for plastic deformation; see Fig. 1. The derived electron wind-dislocation push coefficient B_{ew} was in accord with theoretical predictions (Fig. 2) and with the electron drag coefficient given in the literature.

2.1.2 Phase Transformations

Electropulsing influenced the microstructure of amorphous Fe-Si-B alloys at temperatures well below the normal crystallization temperature [4]. In the alloy having the least B, α-Fe particles ~ 3 nm in size precipitated from the amorphous matrix giving a change in internal magnetic field determined by Mössbauer spectroscopy.

An order of magnitude decrease in the colony size of eutectic Pb-Sn castings was produced by high density electric current pulsing during solidification [5]; see Fig. 3. The major effect of the current pulsing was concluded to be on the nucleation rate.

2.2 Electric Field Effects

2.2.1 Metals

An external dc electric field of ~ 1 kV/cm enhanced the formation of the whiskers shown in Fig. 4, which developed during the superplastic deformation of 7475 Al [6]. These whiskers represent *strains of the order of 10 to 100*. The mechanism responsible for such large strains is not clear and needs further investigation.

2.2.2 Ceramics

2.2.2.1 Mechanical Properties: A dc electric field of the order of 1 kV/cm produced the following effects during the plastic deformation of *polycrystallization NaCl* [7–11]: (a) reduced the flow stress at 0.25 – 0.75 T_M (Fig. 5), (b) raised the brittle-to-ductile transition temperature (Fig. 6) and (c) increased the ductility in tension at 0.75 T_M (Fig. 7). The field strengths at which these effects occurred are *one-to-two orders of magnitude lower* than previously reported to have an influence on dislocation activity in NaCl single crystals tested in Stages I and II of the stress-strain curve. Evaluation of the results gave that

the field enhanced cross slip by a reduction in stacking fault energy, thereby reducing the splitting width of the pertinent dislocations.

An orthogonal electric field of 1 kV/cm along with an axial electrical density current of ~ 1 A/cm^2 produced the following effects during the superplastic deformation of 3Y-TZP in tension at 1450° – 1600°C: (a) reduced the flow stress (Fig. 8), (b) increased the elongation (Figs. 8 and 9), (c) retarded grain growth (Fig. 10) and (c) retarded cavitation (Fig. 11) [12–14]. Three factors were found to play a role in the reduction of the flow stress: (a) Joule heating, (b) the current flow along the specimen gage length and (c) the external field acting perpendicular to the specimen axis. The effect of Joule heating was minor at 1450° and 1500°C, but became important at 1600°C due to the increase in conductivity. Although the exact mechanism by which the combined field and current affected the flow stress, grain growth and cavitation in 3Y-TZP is not clear at this time, it is no doubt associated with the electric charges on the ions and on the crystal defects (space charges) involved in the pertinent processes.

It was found that significant reductions in the flow stress of fine grain size MgO (Fig. 12) and Al_2O_3 (Fig. 13) also occurred for a contacting axial field of 1 kV/cm. Time ran out before the tests required to separate the effects of Joule heating from those of the field and associated electric current *per se* could be performed.

2.2.2.2 Grain Growth: Similar to the effect of an electric field on grain growth in 3Y-TZP shown in Fig. 10, it was found that an axial electric field of 1 kV/cm retarded both static and dynamic grain growth in NaCl at 0.75–0.85 T_M (Fig. 14) [15]. It also prevented the secondary recrystallization which occurred for dynamic grain growth without the field. The exact mechanism for the field effects are not clear, but again they are no doubt associated with charged ions and defects.

2.2.2.3 Specimen Preparation: Techniques were developed for the preparation of test specimens, including: (a) casting and extruding NaCl and (b) pressing and sintering 3Y-TZP, Al_2O_3 and MgO powders [16]. In the case of the three oxides, tensile specimens were cold pressed and sintered to final geometry and dimensions, eliminating the expensive machining operations normally required.

2.3 Interactions with Other Government Agencies and Industry

2.3.1 The Naval Research Laboratory, Washington, DC

An exploratory research project on the electroplastic effect in cast TiAl was sponsored by Dr. Carlos Sanday of the Naval Research Laboratory [17]. An external electric field of 2 kV/cm applied during compression tests produced a 23–47% reduction in the yield stress, which was followed by an 8–33% increase in subsequent strain hardening; the flow stress at 10% strain was however still below that without the field (Fig. 15). In contrast, electropulsing increased both the yield stress and strain hardening, so that the flow stress at 10–20% strain was higher with electropulsing compared to without (Fig. 16). The results suggested that the observed electroplastic effects were due to changes in the stacking fault energy and/or antiphase boundary energy in the γ-TiAl lamellae, thereby influencing deformation twinning.

2.3.2 Magnetic Processing Systems, Inc., Eden Prarie, MN

An exploratory research project was undertaken in collaboration with Magnetic Processing Systems, Inc. on the possibility of extending the fatigue life of steels by magnetically pulsing a specimen following cyclic loading to about 50% of its normal fatigue life. It was found that the *magnetic pulsing prolonged* the fatigue life of low-carbon steel specimens beyond that of specimen fatigued to failure without the intermediate magnetic pulsing treatment [18]. This result with a pulsed magnetic field is in contrast to reports in the literature that the

fatigue life of steel specimens is *reduced* by the presence of a *continuous* magnetic field during the entire test. The mechanism appears to be a rearrangement of the dislocations into a less damaging structure due to magnetostrictive forces.

2.3.3 IAP Research, Inc., Dayton, OH

Exploratory studies were performed on the effects of an external electric field of 3–10 kV/cm on the sintering of iron powder compacts. It was found that the field *reduced porosity by as much as 29 to 73%* compared to sintering without a field, the magnitude depending on the location of the measurement, the effect being greatest at the specimen surface [19]. It was concluded that the reduction in porosity resulted from a decrease in chemical potential of vacancies at or near the specimen surface thereby providing a driving force for migration of vacancies from the pores to the surfacae.

3. Publications and Technical Reports

3.1 Publications

(1) Z. H. Lai, Y. S. Chao, H. Conrad and K. Chu, "Hyperfine Structure Changes in Iron-Base Amorphous Alloys Produced by High Current Density Electropulsing", J. Mater. Res. 10 900–906 (1995).

(2) J. P. Barnak, A. F. Sprecher and H. Conrad, "Colony (Grain) Size Reduction in Eutectic Pb-Sn Castings by Electropulsing", Scripta Metall. Mater. 32 879–884 (1995).

(3) Wei-di Cao and H. Conrad, "Effects of Stacking Fault Energy and Temperature on the Electroplastic Effect in FCC Metals", in Micromechanics of Advanced Materials, TMS, Warrendale, PA (1995) p. 225–236.

(4) H. Conrad and Wei-di Cao, "Plastic Deformation Kinetics of Polycrystalline FCC Metals at Low Homologous Temperatures ($T < 0.4\ T_M$)" in The Johannes Weertman Symposium, TMS, Warrendale, PA (1996) p. 321–327.

(5) Wei-di Cao, X. P. Lu and H. Conrad, "Whisker Formation and the Mechanism of Superplastic Deformation", Acta Mater. 44 697–706 (1996).

(6) Di Yang and H. Conrad, "Effect of an Electric Field on the Plastic Deformation and Fracture of Polycrystalline NaCl, Mater. Sci. Engr. A225 173–183 (1997).

(7) Di Yang and H. Conrad, "Electroplastic Effect in Cast Polycrystalline NaCl with Various Orientations of the Electric Field", J. Am. Ceram. Soc. 80 1389–1396 (1997).

(8) Di Yang and H. Conrad, "Enhancement of the Ductility of Polycrystalline NaCl by an Electric Field", Scripta Mater. 37 767–771 (1997).

(9) Di Yang and H. Conrad, "Influence of an Electric Field on the Superplastic Deformation of 3Y-TZP", Scripta Mater. 36 1431–1435 (1997).

(10) H. Conrad and Di Yang, "The Rate-Controlling Mechanism(s) during Plastic Deformation of Polycrystalline NaCl at 0.28 – 0.75 T_M", submitted J. Mater. Sci.

(11) Di Yang and H. Conrad, "Influence of an Electric Field on the Plastic Deformation of Polycrystalline NaCl at Elevated Temperatures", submitted Acta Mater.

(12) Di Yang and H. Conrad, "Effect of Grain Size on the Electroplastic Effect in NaCl", submitted Proc. Brit. Ceram. Sci.

(13) Di Yang and H. Conrad, "Influence of an Electric Field on Static and Dynamic Grain Growth in NaCl", submitted Scripta Mater.

(14) Di Yang and H. Conrad, "Electrode Arrangement and the Electroplastic Effect during the Superplastic Deformation of 3Y-TZP, to be submitted J. Am. Cer. Soc.

(15) Di Yang and H. Conrad, "Electric Field Enhanced Superplasticity in 3Y-TZP" to be submitted J. Mater. Sci.

(16) Di Yang, C. Sunday and H. Conrad, "Exploratory Study into the Effects of an Electric Field and of Electropulsing on the Plastic Deformation of TiAl", to be submitted to Scripta Mater.

(17) Y. Fahmy and H. Conrad, "Prolonged Fatigue Life of a Low-Carbon Steel by Magnetic Pulsing", to be submitted to Scripta Mater.

3.2 Technical Reports

(1) H. Conrad, "Influence of Electric Currents and Fields on the Kinetics and Microstructure of Phase Transformations in Metals and Ceramics", ARO Interim Progress Report 1/1/95 – 12/31/95, Jan. 19, 1996.

(2) H. Conrad, ibid., ARO Interim Progress Report 1/1/96 – 12/31/96, Jan. 10, 1997.

4. Scientific Personnel

P.I.: Dr. Hans Conrad, Professor Emeritus, NCSU

Faculty Associate: Dr. J. Kasichainula, Research Assoc. Professor

	Graduate Students	Post Doctorals	Visiting Scholars
1.	*Mr. James Campbell* M.S. 1993; Ph.D. expected (1997)	Dr. Z. Guo Dr. Y. Fahmy	Dr. Di Yang
2.	*Mr. James Barnak* M.S. 1993		
3.	*Ms. Debra Mercurio* M.S. expected		

5. Inventions

None

6. Bibliography

1. H. Conrad, "A Study into the Mechanisms for the Electroplastic Effect in Metals and Its Application to Metalworking, Processing and Fatigue", Final Report U. S. ARO Document DAAL03–86–K–0015, March 10, 1989.
2. H. Conrad, "A Study into the Effects of Electric Fields and Currents on the Aging and Quench Hardening of Steels", Final Report, U. S. ARO Document DAAL03–89–K–0115, January 15, 1993.
3. Wei-di Cao and H. Conrad, in Micromechanics of Advanced Materials, ed. by S. Chu et al, TMS, Warrendale, PA (1995) p. 225.
4. Z. Lai, Y. Chao, H. Conrad and K. Chu, J. Mater. Res. 10 900 (1995).
5. J. Barnak, A. Sprecher and H. Conrad, Scripta Metall. Mater. 32 879 (1995).
6. Wei-di Cao, X. P. Lu and H. Conrad, Acta Mater. 44 697 (1996).
7. Di Yang and H. Conrad, Mater. Sci. Engr. A225 173 (1997).
8. Di Yang and H. Conrad, J. Am. Ceram. Soc. 80 1389 (1997).
9. Di Yang and H. Conrad, Scripta Mater. 37 767 (1997).
10. Di Yang and H. Conrad, "Influence of an Electric Field on the Plastic Deformation of Polycrystalline NaCl at Elevated Temperatures", submitted to Acta Mater.
11. Di Yang and H. Conrad, "Effect of Grain Size on the Electroplastic Effect in NaCl", submitted to Proc. British Ceram. Soc.
12. Di Yang and H. Conrad, Scripta Mater. 36 1431 (1997).
13. Di Yang and H. Conrad, "Electrode Arrangement and the Electroplastic Effect during the Superplastic Deformation of 3Y-TZP", to be submitted to J. Amer. Ceram. Soc.
14. Di Yang and H. Conrad, "Electric Field Enhanced Superplasticty in 3Y-TZP", to be submitted to J. Mater. Sci.

15. Di Yang and H. Conrad, "Influence of an Electric Field on Static and Dynamic Grain Growth in NaCl", submitted to Scripta Mater.

16. Di Yang, J. Campbell and H. Conrad, "Preparation of NaCl, 3Y-TZP, Al_2O_3 and MgO Specimens for Mechanical Testing", unpublished research NCSU (1996).

17. Di Yang and H. Conrad, "Exploratory Study into the Effects of an Electric Field and of Electropulsing on the Plastic Deformation of TiAl", to be submitted to Scripta Mater.

18. Y. Fahmy and H. Conrad, "Prolonged Fatigue Life of a Low-Carbon Steel by Magnetic Pulsing", to be submitted to Scripta Mater.

19. Y. Fahmy and H. Conrad, "Electrosintering of Iron Powder Compacts", Report to IAP, October 18, 1996.

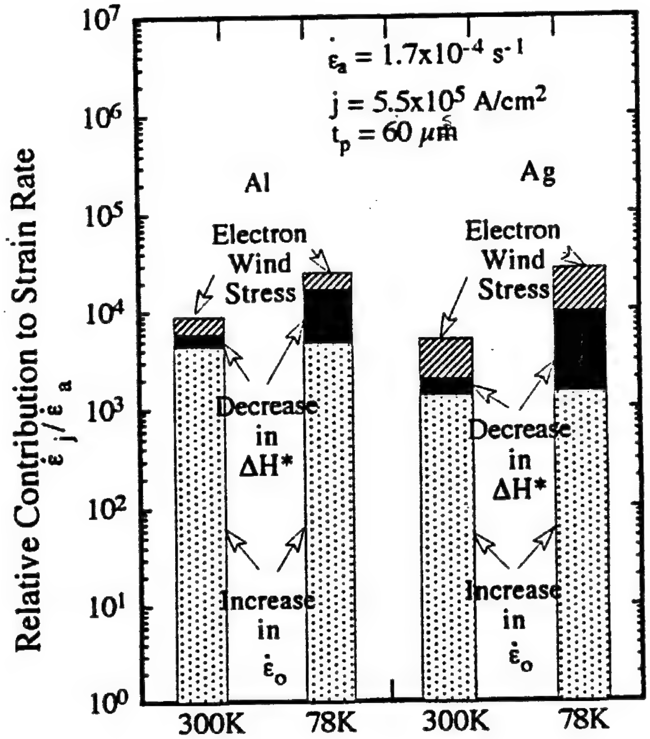


Fig. 1 The relative contributions to the electroplastic effect in Al and Ag at 78 and 300K [3].

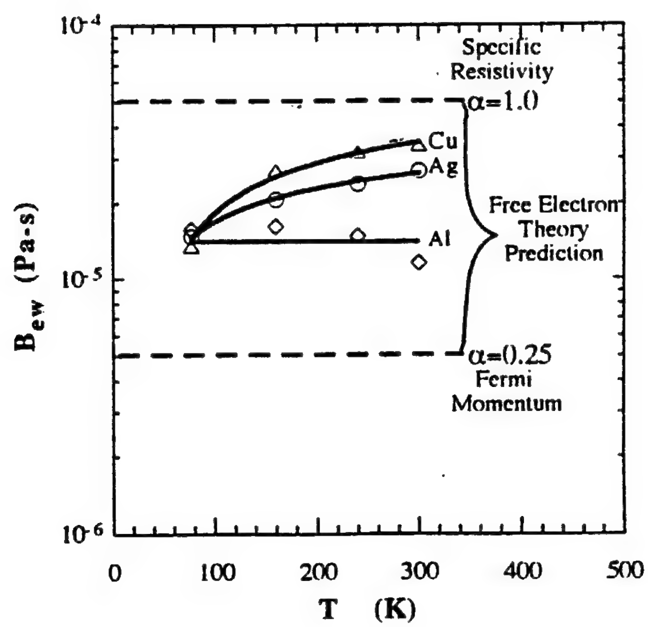
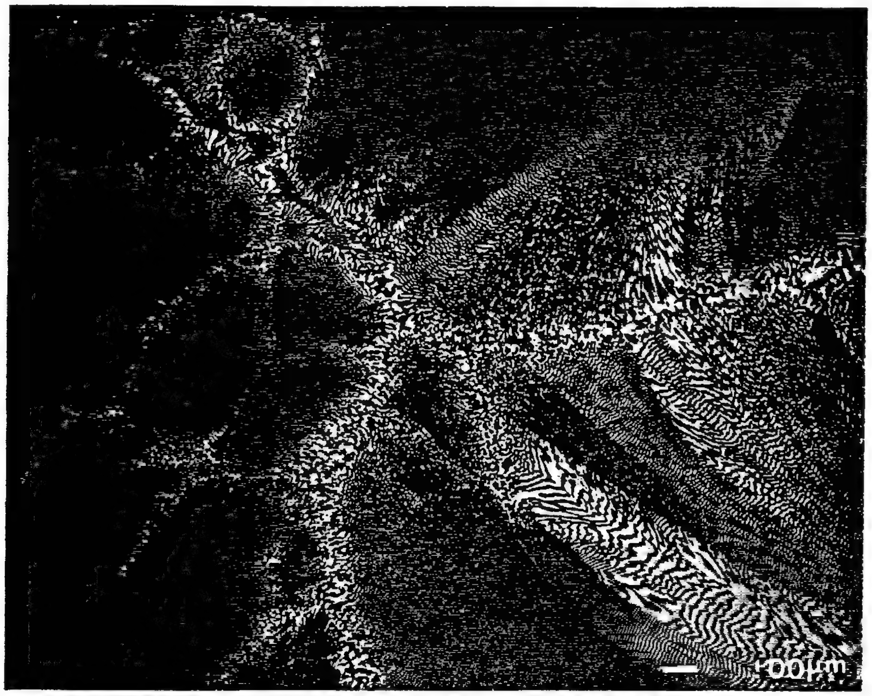
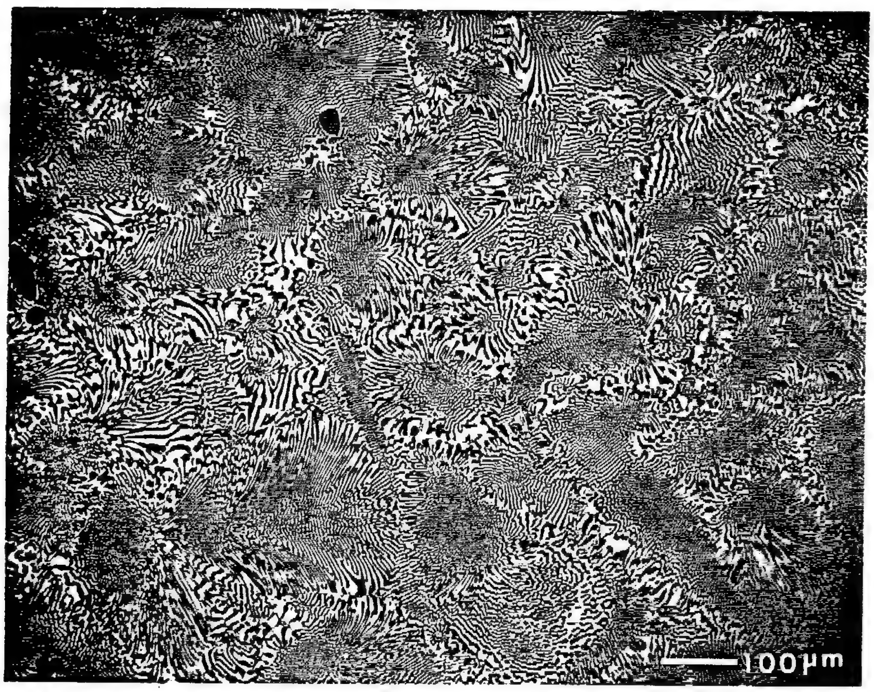


Fig. 2 Comparison of the measured electron wind push coefficient B_{ew} with theoretical predictions [3].



a.



b.

Fig. 3 Optical micrographs illustrating the effect of electropulsing on the as-cast structure of 60Sn40Pb [5]: (a) no current and (b) electropulsed with 1428 A/cm^2 for 60 μs and 1.5 pulses per s. Dark phase in Pb-rich; light phase is Sn-rich.

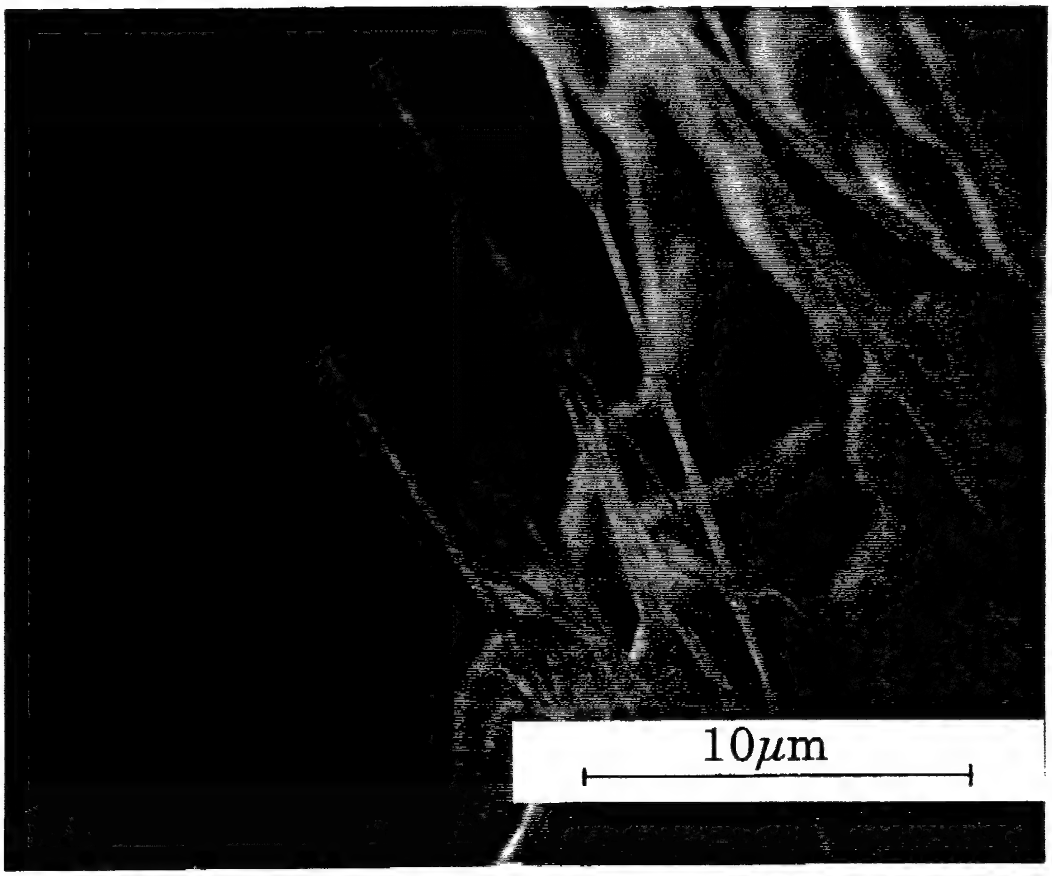


Fig. 4 SEM micrograph showing the nature of whiskers which formed during the superplastic deformation of 7475 Al [6].

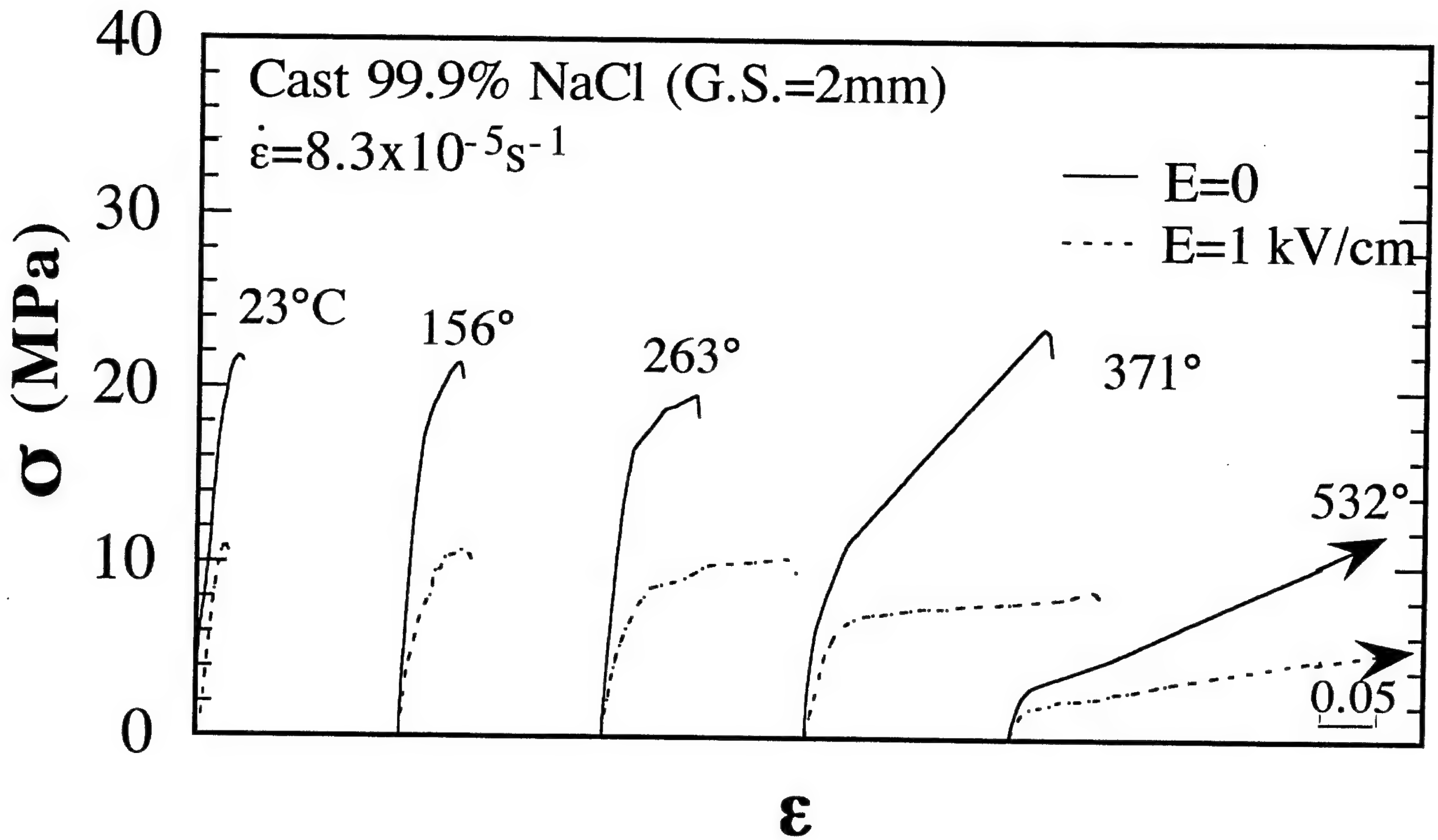


Fig. 5 Effect of temperature on the stress-strain curves of polycrystalline NaCl in compression without and with a contacting, axial electric field E = 1 kV/cm [10].

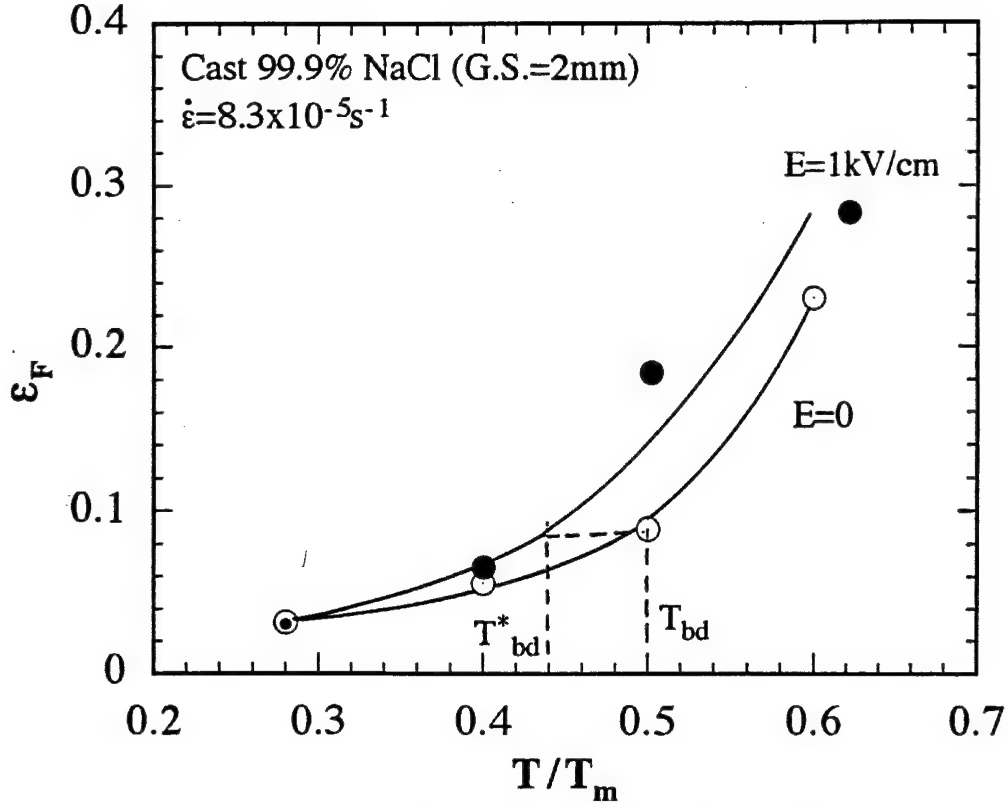


Fig. 6 Effect of a contacting, axial electric field E = 1 kV/cm on the brittle-to-ductile transition temperature T_{bd} of polycrystalline NaCl [10]. The indicated temperatures with the field include the rise due to Joule heating.

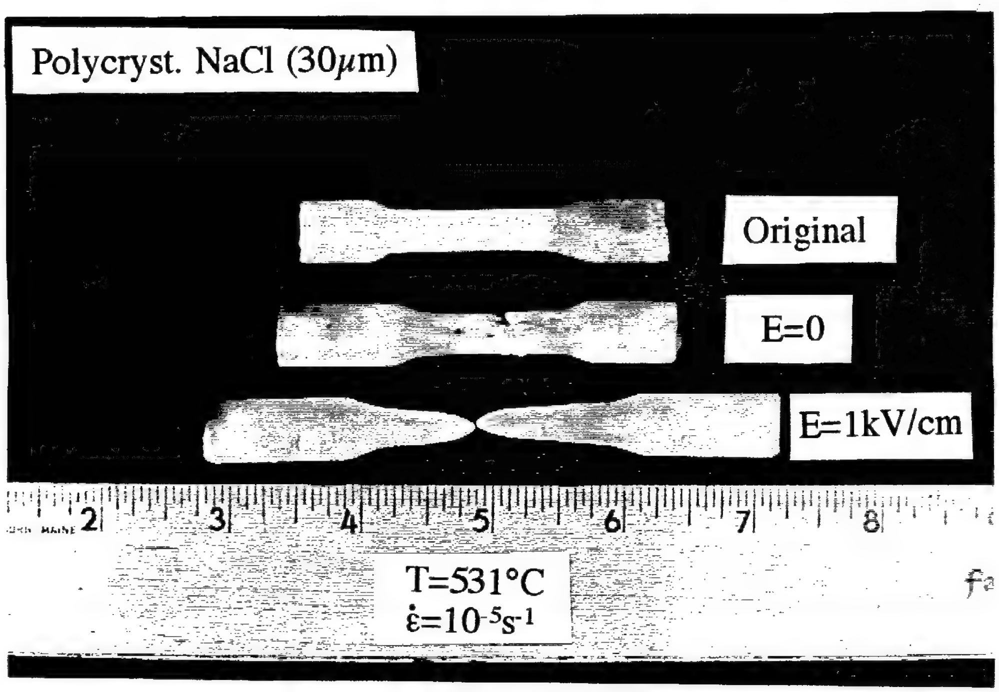


Fig. 7 Photograph showing the effect of a non-contacting, radial electric field E = 1 kV/cm on the ductility of polycrystalline (d_o = 30 μm) NaCl at 532°C (0.75 T_M) [9].

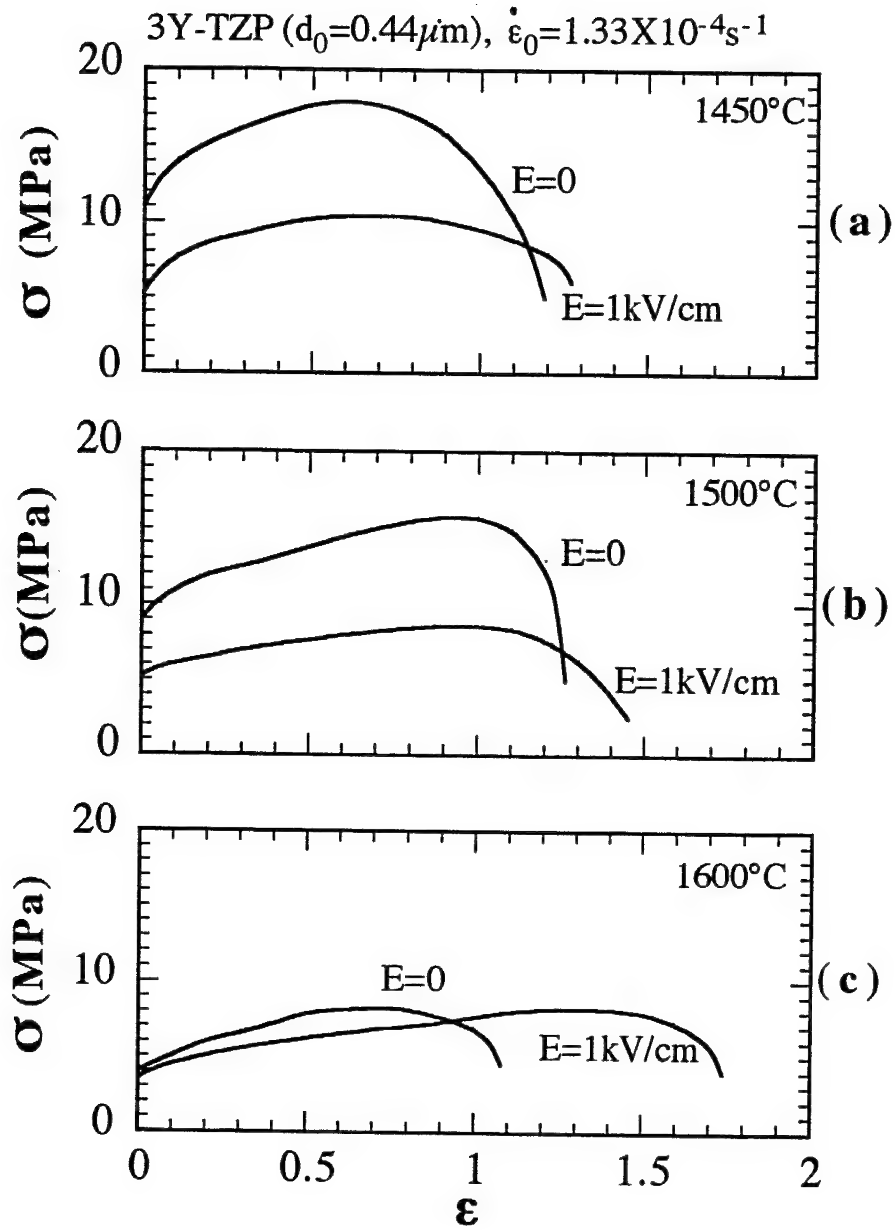


Fig. 8 Effect of a non-contacting, orthogonal electric field E = 1 kV/cm on the true stress-strain curve of 3Y-TZP at 1450°, 1500° and 1600°C.

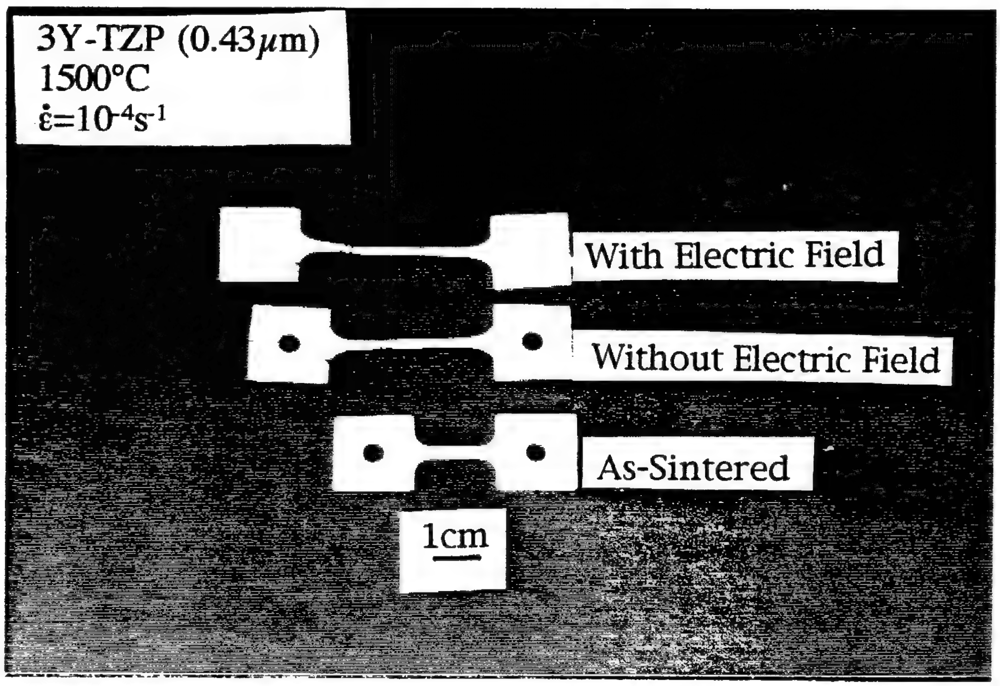


Fig. 9 Photograph showing the effect of a non-contacting, orthogonal electric field E = 1 kV/cm on the ductility of 3Y-TZP at 1500°C [12].

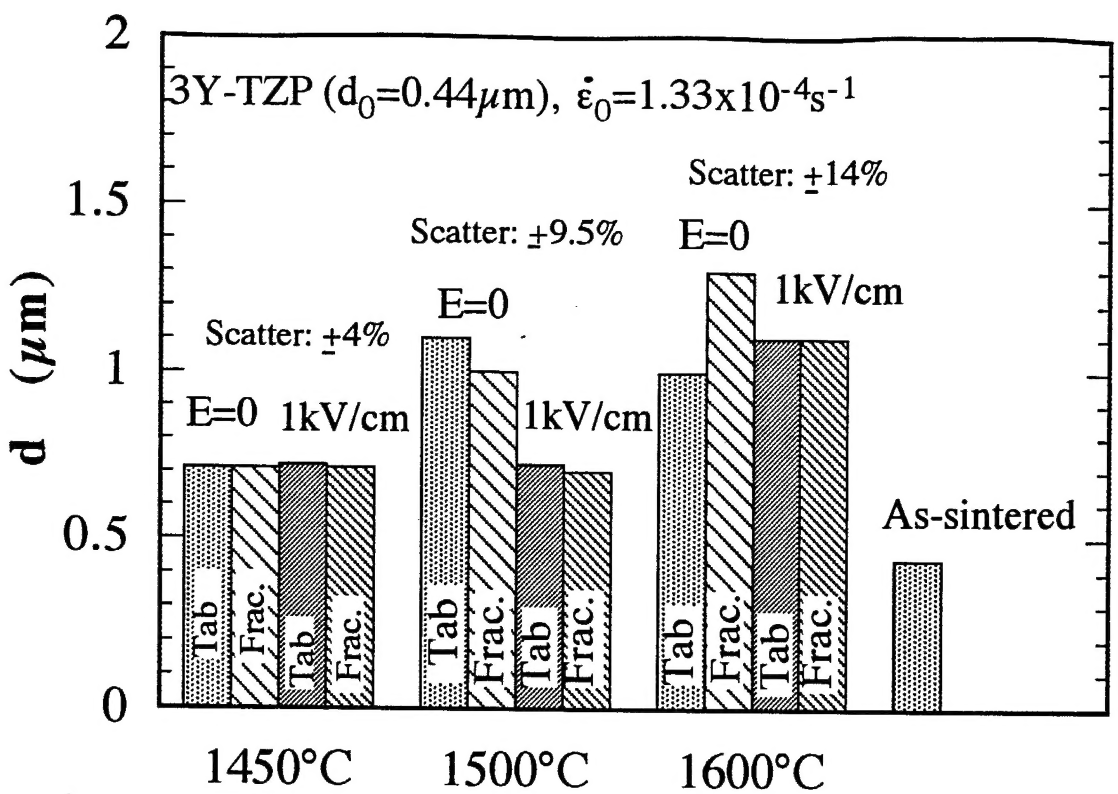


Fig. 10 Effect of a non-contacting, orthogonal electric field E = 1 kV/cm on grain growth during superplastic deformation of 3Y-TZP at 1450°, 1500° and 1600°C. Tab indicates grip region; fracture indicates region near the fracture surface.

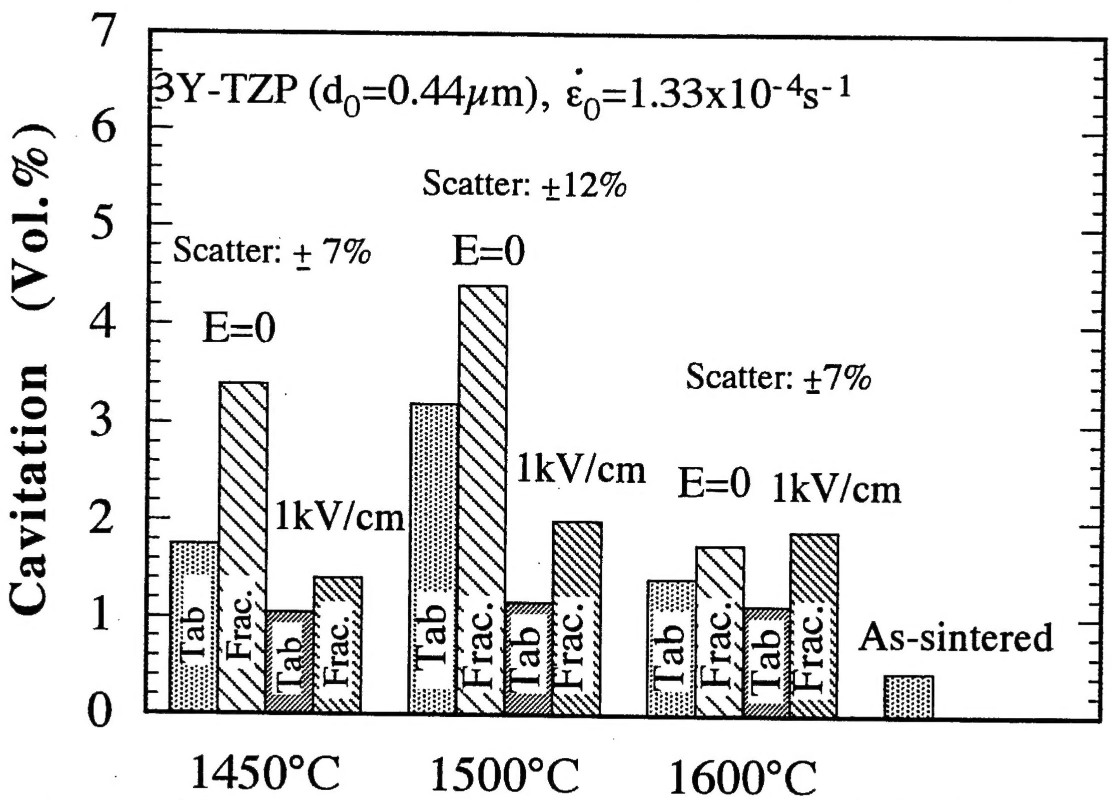


Fig. 11 Effect of a non-contacting, orthogonal electric field E = 1 kV/cm on cavitation during superplastic deformation of 3Y-TZP at 1450°, 1500° and 1600°C. Tab indicates grip region; fracture indicates region near the fracture surface.

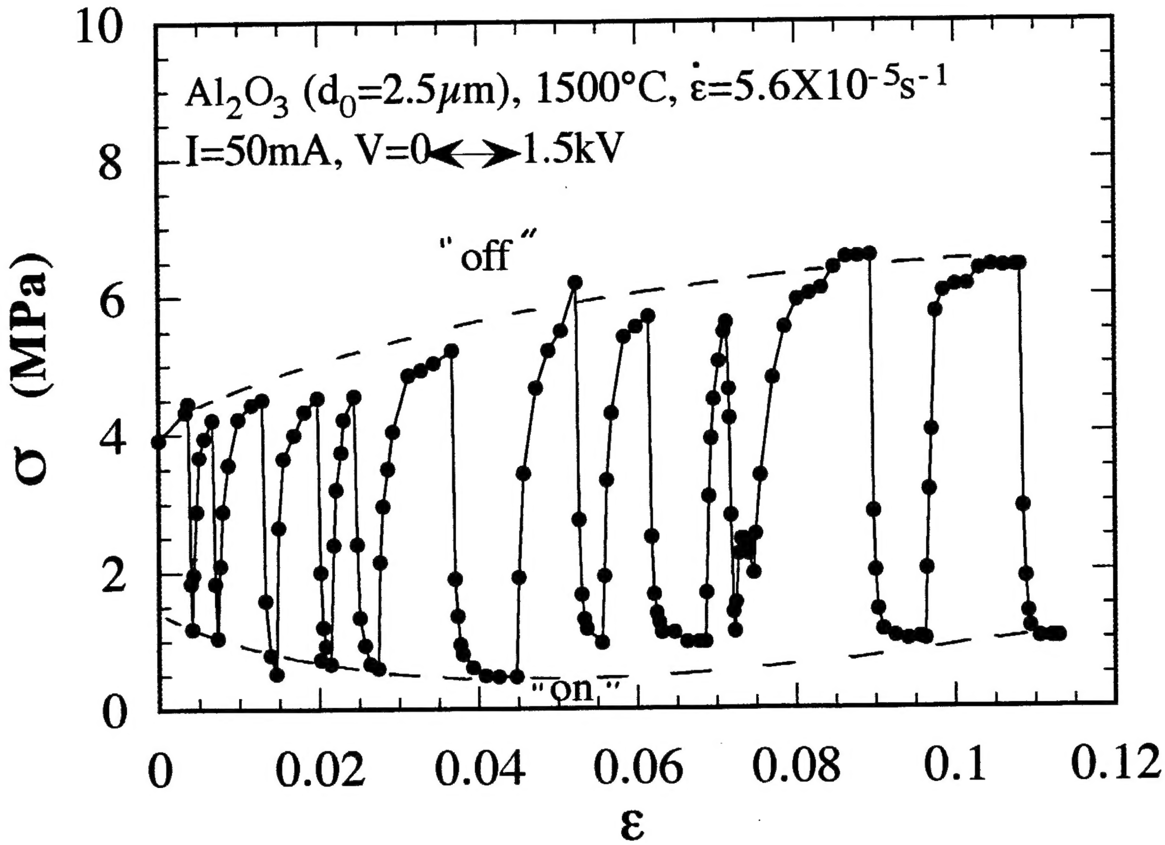


Fig. 12 Effect on the flow stress of turning a contacting, axial electric field E = 1 kV/cm "on" and "off" during the deformation of Al_2O_3 at 1500°C.

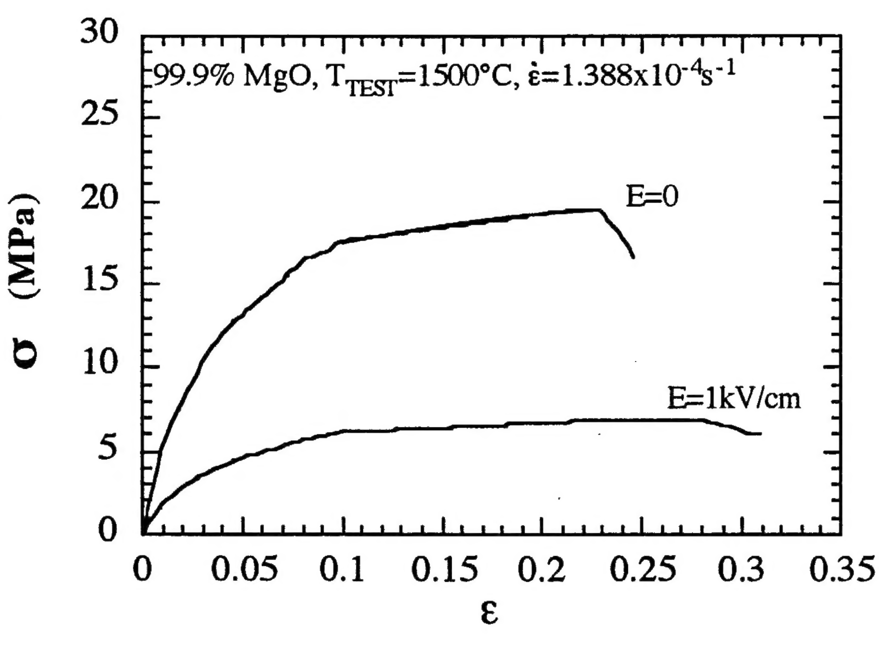


Fig. 13 Effect of a contacting, axial electric field E = 1 kV/cm on the true stress-true strain curve of MgO at 1500°C.

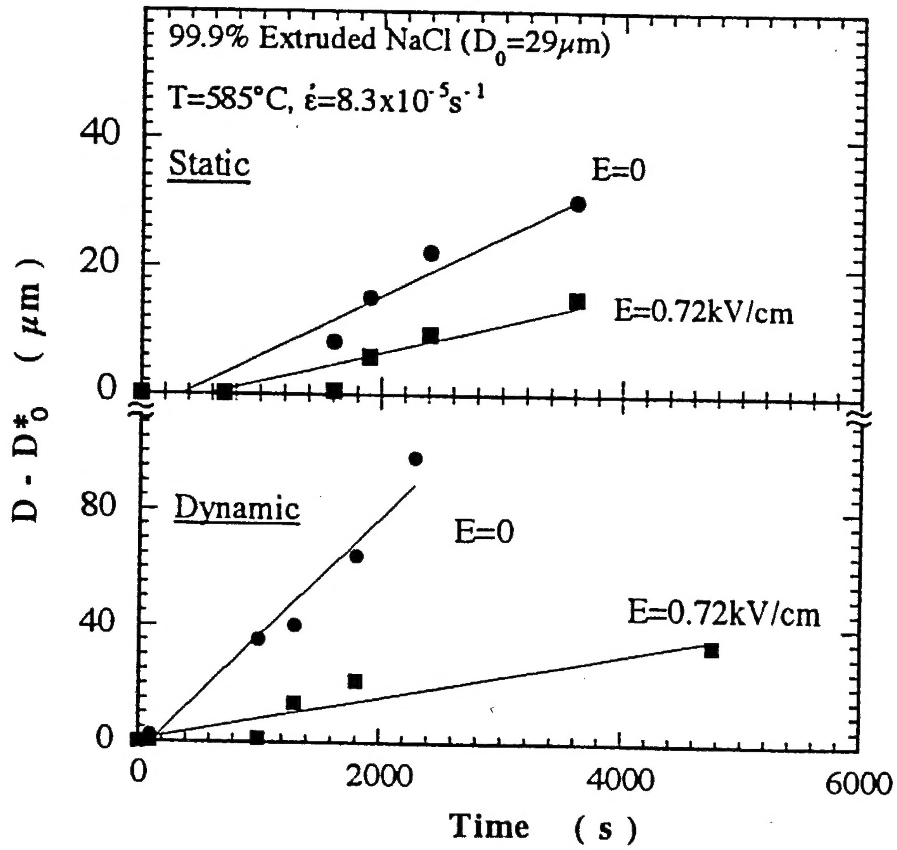


Fig. 14 Effect of a non-contacting, radial electric field E = 0.72 kV/cm on static and dynamic grain growth in extruded NaCl at 585°C (0.80 T_M) [15].

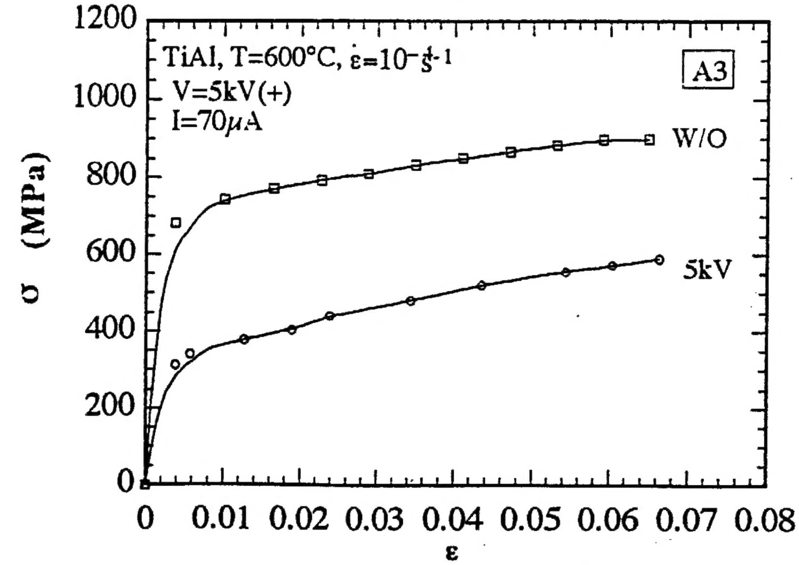


Fig. 15 Effect of a non-contacting, radial electric field E = 2 kV/cm on the true stress-strain curve of cast TiAl in compression at 600°C [17].

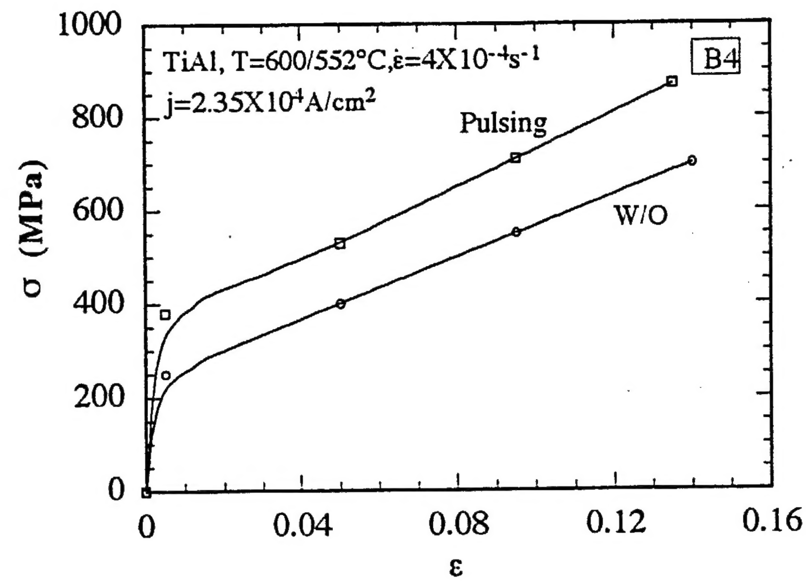


Fig. 16 Effect of electropulsing on the true stress-strain curve of cast TiAl in compression at 600°C [17].